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Mapping Tasmania's cultural landscapes: Using habitat suitability modelling of archaeological sites as a landscape history tool

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Abstract

Aim: Understanding past distributions of people across the landscape is key to understanding how people used, affected and related to the natural environment. Here, we use habitat suitability modelling to represent the landscape distribution of Tasmanian Aboriginal archaeological sites and assess the implications for patterns of past human activity.

Location: Tasmania, Australia.

Methods: We developed a RandomForest 'habitat suitability' model of site records in the Tasmanian Aboriginal Heritage Register. We applied a best-effort bias correction, considered 31 predictor variables relating to climate, topography and resource proximity, and used a variable selection procedure to optimize the final model. Model uncertainty was assessed via bootstrapping and we ran an analogous MaxEnt model as a cross-validation exercise.

Results: The results from the RandomForest and MaxEnt models are highly congruent. The strongest environmental predictors of site occurrence include distance to coast, elevation, soil clay content, topographic roughness and distance to inland water. The highest habitat suitability scores are distributed across a wide range of environments in central, northern and eastern Tasmania, including coastal areas, inland water body margins and forests and savannas in the drier parts of Tasmania. With the exception of coastal areas much of western Tasmania has low habitat suitability scores, consistent with theories of low-density Holocene Tasmanian Aboriginal settlement in this region.

Main conclusions: Our modelling suggests Tasmanian Aboriginal people occupied a heterogeneity of habitats but targeted coastal areas around the whole island, and drier, less steep and/or open forest and savanna environments in the central lowlands. The western interior was identified as being rarely used by Aboriginal people in the Holocene, with the exception of isolated pockets of habitat; yet whether this is a true reflection of Aboriginal-resourceuse demands increased archaeological surveys, particularly in the Tasmanian Wilderness World Heritage Area.

KEYWORDS

archaeology, Australia, fire, habitat suitability, RandomForest, Tasmanian Aboriginal people

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1 | INTRODUCTION

All human populations, past and present, tend towards particular patterns of biogeographical distribution. Describing these patterns is key to understanding the role of people in landscape history because they underlie how, when, where and to what degree people shaped the course of landscape evolution. Geographical analysis of archaeological materials can thus make an important contribution to developing coherent narratives of the coupled human and environmental past.

In Tasmania, the distribution of Tasmanian Aboriginal people prior to European invasion is core to a number of pressing questions in the island's biogeography, ecology, conservation and cultural history.

Key issues include the extent to which Tasmanian Aboriginal hunting, gathering and fire use influenced the structure, function and distribution of modern plant and animal communities (Bowman, Wood, Neyland, Sanders, & Prior, 2013; Folco & Kirkpatrick, 2013; Fletcher & Thomas, 2007a; Jackson, 1999; Mariani et al., 2017; Thomas & Kirkpatrick, 1996). Indeed, where and how Aboriginal people burned the landscape, and the extent to which this had landscape-scale impacts on the island's biota, has long placed Tasmania at the centre of global archaeological and fire ecology debates (Bowman, Perry, & Marston, 2015; Jackson, 1968; Jones, 2017; McWethy et al., 2013). Past human impacts on Tasmania's environment thus remain a question with significant and urgent implications for conservation and landscape management today (Bowman & Perry, 2017; French, Prior, Williamson, & Bowman, 2016; Marris, 2016).

At its broadest level, understanding the biogeography of Tasmanian Aboriginal resource use is fundamental to our capacity to understand and manage Tasmania as a *cultural landscape*: for Tasmanian Aboriginal and non-Aboriginal people to move together towards culturally sensitive conservation and land management regimes (and landscape narratives) that recognize and account for the long-term Tasmanian Aboriginal presence. Although efforts in this area are increasing, they remain hampered by uncertainty about the timing, intensity and nature of past Tasmanian Aboriginal resource use in different landscape units. This lack of knowledge has been a particular issue in the rugged south-western interior of the Tasmanian World Heritage Wilderness Area (TWWHA). In this area, a protracted debate over the extent and biogeographical distribution of Holocene Tasmanian Aboriginal occupation has fuelled uncertainty in cultural heritage management, and the extent to which anthropogenic burning is responsible for the extensive tracts of buttongrass moorland in this perhumid climatic zone (Bowman & Perry, 2017; Cosgrove, 1999; DPIPWE, 2012; Fletcher & Thomas, 2010; Mariani et al., 2017).

A key to these discussions is understanding the geographical patterns of past Tasmanian Aboriginal people, yet to date there has been no holistic biogeographical assessment of Holocene Tasmanian Aboriginal settlement. A biogeographical model exists for late Pleistocene occupation (*ca* 40,000–13,000 BP), which

in essence posits that Tasmanian Aboriginal people of this period heavily concentrated their activities in fertile, sheltered grassland pockets in river valleys in the island's south (Allen, Cosgrove, & Garvey, 2016; e.g. Cosgrove, 1999). This empirically and theoretically grounded model has strong archaeological value, but speaks to a period when the climate and resource ecology of Tasmania was vastly different to today: the climate was significantly cooler and drier, sea levels lower, and both the nature and distribution of vegetation communities were dramatically distinct (e.g. D'Costa, Grindrod & Ogden, 1993; Mackenzie & Moss, 2014; Petherick, Whitlock & Haberle, 2013; Stahle Whitlock & Haberle, 2016). This model therefore tells us little about the Tasmanian Aboriginal biogeography of Holocene Tasmania, the period most relevant to understanding the legacy of Tasmanian Aboriginal land use on Tasmania's modern landscape.

Settlement patterns in Holocene Tasmania have been much less clearly articulated and much more subject to debate, and how Tasmanian Aboriginal people distributed themselves across the island has never been holistically evaluated. Instead, research has been limited to regional-scale assessments based on local archaeological surveys, ethnographic data and/or traditional knowledge (e.g. Cameron, 2011; Kee, 1990; Thomas, 1983; Thomas, 1992). While there is general agreement that people increasingly occupied eastern, northern and coastal areas (which became increasingly resource rich as the climate warmed), debate continues as to the extent, or reality, of "abandonment" of the SW interior (DPIPWE, 2012; Fletcher & Thomas, 2010) and overall the ecological contours of Tasmanian Aboriginal activity are poorly understood. For instance, important questions remain over the nature and intensity of resource exploitation (and burning) of dry and wet forest, coastal and open grassy woodland zones (e.g. Thomas, 1992). This poorly resolved understanding impedes the development of a coherent understanding of the biogeography of Tasmania, particularly the environmental controls of fire-sensitive taxa.

In this paper, we address this gap by applying habitat suitability modelling to the most comprehensive set of records of past Tasmanian Aboriginal activity—the archaeological site records in the Aboriginal Heritage Register (AHR)—to disclose the biogeographical patterns of Tasmanian Aboriginal occupancy. Habitat suitability modelling builds quantitative models of site–environment (or species–environment) relationships from observational data and uses these to estimate habitat suitability—and by inference, likelihood of occurrence—across a landscape (Elith et al., 2006; Franklin, Potts, Fisher, Cowling, & Marean, 2015). Originally developed for ecological applications, habitat suitability modelling can be adapted to meet a wide range of purposes and has strong potential as a biogeographical, palaeoecological and archaeological tool (d'Alpoim Guedes, Crabtree, Bocinsky, & Kohler, 2016; Franklin et al., 2015).

As our base model we use RandomForest (Liaw & Wiener, 2002), an ensemble decision tree method based on classification and regression tree algorithms. RandomForests are widely recognized for their capacity to produce good predictive models, are robust to over



fitting and make few assumptions about the distribution of variables (Howard, Stephens, Pearce-Higgins, Gregory, & Willis, 2014). They have consistently performed well in comparisons of habitat suitability modelling techniques (Hollings, Robinson, van Andel, Jewell, & Burgman, 2017; Mi, Huettmann, Guo, Han, & Wen, 2017; Stelmaszczyk-Górska et al., 2015), accommodate complex interactions between response and predictor variables, and perform well with limited and/or spatially biased presence data (as available here). In order to maximize confidence, we also apply another commonly used habitat suitability model, MAXENT (Elith et al., 2006, 2011), as a cross-validation tool.

We apply a best-effort bias correction to account for the impact of differential survey effort on the archaeological record (Merow, Smith, & Silander, 2013) and limit our analysis to artefact sites (as opposed to, for example, rock engravings and burials) on the basis that these provide the simplest proxy for where people were, most often, through time. We assume that with a few key exceptions, our model will reflect Holocene archaeological deposition patterns and therefore Holocene Tasmanian Aboriginal activity because the overwhelming majority of artefact sites are isolated artefacts and artefact scatters found via surface surveys or opportunistic finds (e.g. Kee, 1990; Kee 1991). It is well established that site visibility and taphonomy strongly biases such archaeological assemblages towards younger sites (Surovell, Byrd Finley, Smith, Brantingham, & Kelly, 2009; Williams, Ulm, Cook, Langley, & Collard, 2013); the clear implication is that most artefact sites in the AHR will most likely date from the more recent past, when pollen records from around Tasmania suggest that vegetation communities were broadly similar to those present immediately prior to European settlement (Fletcher & Thomas, 2007b; Jones, Thomas, & Fletcher, 1989; Mackenzie & Moss, 2014; Mariani et al., 2017; Thomas & Hope, 1994). We base our interpretations on this assumption, discussing as necessary known exceptions such as Pleistocene sites in the south-western valleys (e.g. see Cosgrove, 1999; DPIPWE, 2012).

In this way, we seek to produce a biogeographical model of past Tasmanian Aboriginal activity as indicated by the archaeological record. While the archaeological record does not capture some important elements of landscape use (such when in the year sites were occupied), archaeological site records are the most direct available indicator for where and how often people occupied different parts of the Tasmanian landscape. They are, therefore, a pragmatic and appropriate platform upon which to develop and test landscape-scale ideas about the relative intensity of previous human occupation, and inform contemporary management by distinguishing climatic, edaphic and anthropogenic influences on the evolution of Tasmania's landscapes.

We specifically ask:

1. Which types of landscape have the greatest (and least) archaeological evidence for Tasmanian Aboriginal occupation? and
2. What are the ramifications for existing theoretical models of Holocene Tasmanian Aboriginal activity?

2 | MATERIALS AND METHODS

2.1 | Study area

Tasmania is a cool temperate continental island that lies to the south of mainland Australia (40–43°S, Figure 1). At a very broad level, Tasmania can be divided biogeographically into a wet, rugged west and a gentler, drier east: a distinction that is a function of both climatic, geological and topographic factors.

The west comprises an exposed coastline rising to steep and rugged mountain ranges trending NW–SE. These ranges intercept the prevailing mid-latitude westerlies, resulting in a perhumid climate with rainfall of up to 3,500 mm/year (Figure 1). The underlying geology is dominated (particularly in the south) by Precambrian quartzites that produce infertile, siliceous soils, but there are also areas of more fertile limestones and volcanics. Alpine heaths, herbfields and coniferous shrubs dominate above the treeline (ca 750 m above sea level), while below the treeline the vegetation is a complex mosaic of temperate rainforest, wet mixed forests of rainforest and *Eucalyptus* species, and buttongrass moorland (Harris & Kitchener, 2013). This mosaic is governed by a complex interaction of soil fertility, soil drainage and fire, with the relative importance of these factors still a major topic of debate (e.g. Bowman & Perry, 2017).

The east, in contrast, lies in rain shadow, with most areas receiving rainfall of 500–800 mm/year. The relief is lower and gentler, with the main relief feature—the Eastern Tiers—typically reaching just 600–800 m (see Figure 1). The dolerite-dominated geology (granite in the north-east) supports generally fertile soils, although there are also areas of leached sandy substrates. Dry sclerophyll forest dominates, with patches of open sclerophyll woodland and tussock grassland. Exposed hill-tops generally support dry, open *Allocasuarina* woodlands (Fensham, 1989). Soil, fire and local topography are important mediators of fine-scale ecological distributions, with bedrock geology tightly linked to both the over- and under-storey characteristics of the eastern sclerophyll communities (Fensham, 1989; Kirkpatrick & Nunez, 1980).

These two broad biogeographical zones are separated by the Central Plateau, a large area typically 900–1,100 m in elevation that supports a mix of wet and dry sclerophyll woodland at lower elevations, grading upwards into alpine and coniferous forest communities (Harris & Kitchener, 2013). Immediately to the east of the Central Plateau lies the Midlands, Tasmania's only significant inland plain (see Figure 1). Lying between the Central Plateau and the Eastern Tiers, the Midlands is the driest region of Tasmania and supports mainly dry sclerophyll forest and open woodlands (Fensham, 1989).

These biogeographical contrasts have been stable throughout the Holocene and have important implications for resource availability. At a very basic level, it is often argued that the wet, rugged and infertile western interior was both the most climatically hostile environment and the most resource poor, particularly with respect to marsupial game (Allen et al., 2016). Inland water bodies supporting water-fowl and other resources known to be important ethnographically (Cameron, 2011; Hiatt, 1968) are common on the Central

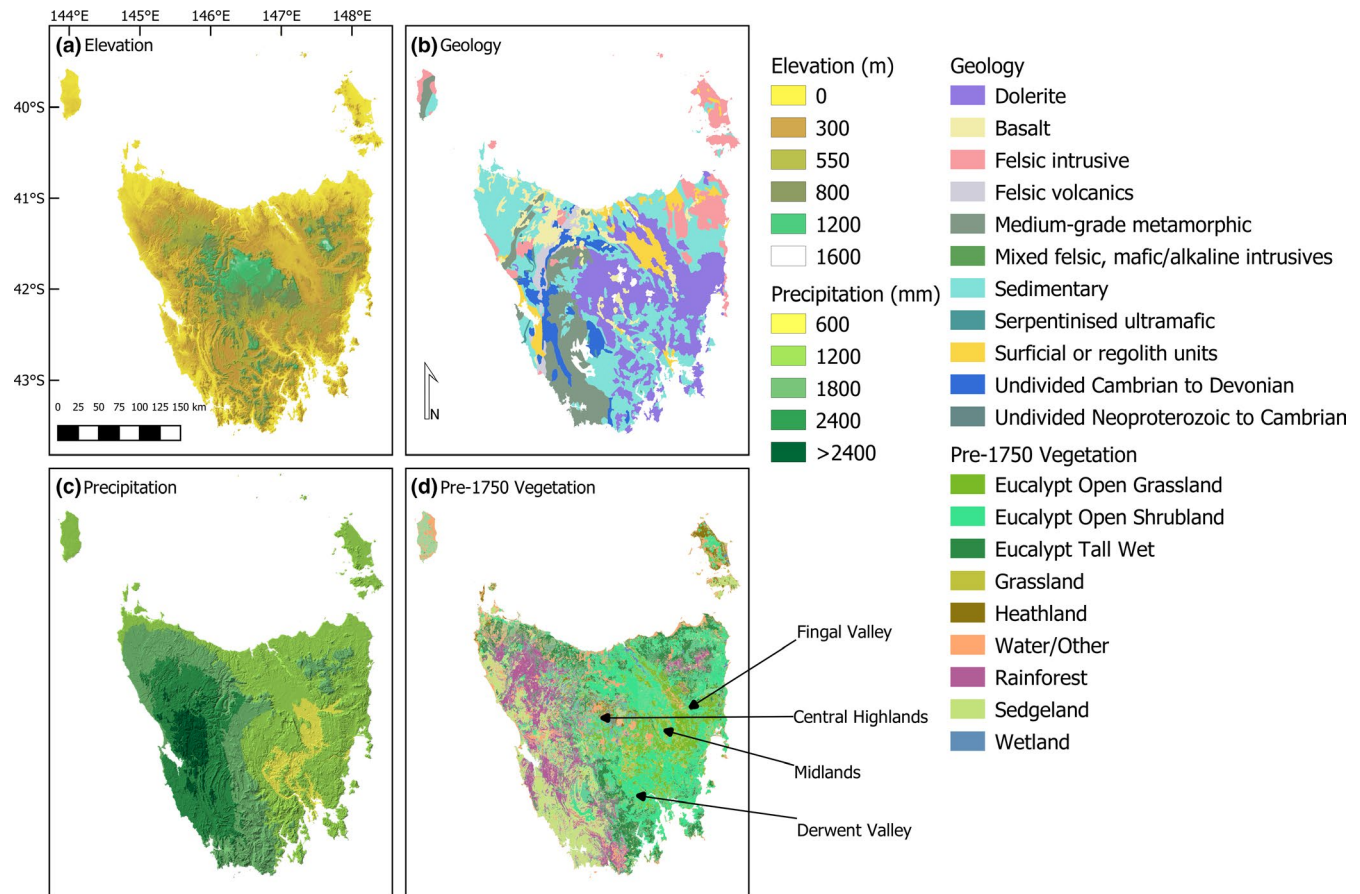


FIGURE 1 Geographical context of the study area showing: (a) elevation across Tasmania; (b) major geological units (Geoscience Australia, 2012); (c) mean annual precipitation derived from the WorldClim 2 dataset (Fick & Hijmans, 2017); (d) reconstructed pre-1750 vegetation communities (Department of the Environment, 2014)

Plateau and to a lesser extent, the Midlands and eastern coastal regions.

2.2 | Source data extraction

We extracted the environmental co-variables from the 8,154 artefact sites in the AHR (isolated artefacts, artefact scatters and mixed site types with artefacts present). A large majority of these data points have a co-ordinate accuracy of ± 50 m or better. A small number have a co-ordinate accuracy of ± 100 m.

The environmental co-variables comprised 31 variables selected to capture a plausible range of environmental parameters likely to influence human decision-making processes and thus “habitat suitability” from a human perspective (reviewed in an Australian context by Ridges, 2010). These variables (see Appendix S1) include aspects of climate, topography, proximity to types of inland water and proximity to a range of vegetation communities; here, used as proxies for resources within each community. In taking this approach we do not deny the role of cultural, spiritual and social drivers of human place attachment, but rather seek to characterize the landscapes people have historically frequented from a biogeographical perspective. We acknowledge that access to mineral resources (e.g. chert and silcrete

for toolmaking, ochre) is also likely to have been important, but we chose not to include these in our model as the available geological maps do not reasonably represent their accessibility to Tasmanian Aboriginal people.

Bioclimatic variables were extracted from the WorldClim2 database (Fick & Hijmans, 2017); geological variables from the Land Information System Tasmania (Department of Primary Industries Water & Environment Tasmania, 2012) and vegetation variables from the Pre-1750 Major Vegetation Subgroups layer in NVIS Version 4.2 (Department of the Environment, 2014). All other variables were derived from layers in the Soils and Landscapes Grid of Australia (Kidd, Webb, Malone, & Minasny, Budiman, McBratney, 2014). Resource proximity was calculated as “cost distance” in order to take the difficulty (time and energy ‘cost’) of traversing a given distance into account (Verhagen & Whitley, 2012). Cost distance was calculated in ArcGIS using a digital elevation model as the cost variable basis. All environmental variables were re-sampled to a 66m pixel resolution so that all layers matched the resolution of the finest spatial input layer.

To protect sensitive site location information, only the environmental co-variables were passed on to the research team. The geolocation data were discarded immediately after the co-variables

had been extracted from the archaeological database by staff of Aboriginal Heritage Tasmania, the data custodian. All analyses were therefore performed with the matrix of environmental co-variables only.

2.3 | RandomForest modelling

We modelled the landscape distribution of all artefact sites in the AHR using the *randomForest* package (Liaw & Wiener, 2002) in R version 3.4.4 (R Development Core Team, 2018). We ran the model in classification mode and model parameters were set to 500 trees grown, with the number of variables per split, sample size and node size set to the *randomForest* function defaults.

We first ran a global model with all 31 environmental co-variables to determine the optimal spatial scale at which to correct for bias (non-random sampling). We based our bias correction on sampling point density (Merow et al., 2013), following the methodology of Kramer-Schadt et al. (2013). Using the presence data, we first constructed four separate kernel density estimate grids in order to test kernel smoothing parameters at 5, 10, 20 and 50 km (Liaw Figure S1.1 in Appendix S1). For each spatial scale we then used the probabilities derived from the kernel density grid to generate an equal number of synthetic background points (pseudo-absences) to the presence points. These background points were used alongside the presence points to train a *RandomForest* model for each of the kernel density spatial scales. We selected the optimal scale for kernel density smoothing on the basis of model AUC scores (Kramer-Schadt et al., 2013).

We then selected the variable set for inclusion in the final model using the variable selection procedure described in Genuer et al. (2010). We specifically used the variant described by the authors for instances where the objective is the interpretation (as opposed to parsimonious prediction) of response variables (see Genuer et al., 2010). Taking the final set of variables selected by the Genuer method, we additionally eliminated the less important variable of each pair of highly correlated variables, defined here as a correlation of >0.80 (Merow et al., 2013).

Our final model was run with the optimal bias correction parameters and this variable subset. We evaluated model performance using the AUC score, kappa score, and out-of-the bag (OOB) error rates and evaluated model uncertainty using bootstrapping with 50×500 random subsets of data points. We evaluated environmental variable contributions using both the algorithm of Genuer et al. (2010) and the suite of variable importance measures (including mean decrease in accuracy and mean decrease in GINI) provided by the *randomForest* package (Liaw & Wiener, 2002).

2.4 | High and low suitability habitat analysis

We characterized those landscapes deemed to be particularly (a) high, or (b) low in habitat suitability by our final model by performing a targeted analysis of their biogeographical characteristics.

For this analysis, we defined “high suitability” as the 20% of pixels with the highest model probability scores and “low suitability”

as the 20% with the lowest scores. The 20% cut-off was designed to capture a breadth of low and high suitability points that would support a useful discussion of the contrasts between more and less frequented habitats. Applying this filter, we performed a descriptive analysis of the biogeographical characteristics of these ‘high’ and ‘low’ suitability data points, in comparison with each other and the remainder of Tasmania, thus characterizing those landscape types with the greatest and least archaeological evidence for utilization by Tasmanian Aboriginal people. We specifically assessed the relative distribution of high and low suitability cells along key environmental gradients (distance to coast, elevation, precipitation and mean annual temperature), and quantified the proportion of each cell type falling into pre-1750 vegetation categories (Department of the Environment, 2014).

2.5 | MaxEnt cross-validation

We ran a *MaxEnt* species distribution model analogous to our final *RandomForest* model to derive more robust conclusions by comparing agreement between the methods. We used *MaxEnt* v. 3.4.0 (Phillips, Anderson, Dudík, Schapire, & Blair, 2017), run within R using the ‘*dismo*’ package (Hijmans, Phillips, Leathwick, & Elith, 2017). We ran *MaxEnt* in Samples With Data mode, allowing all feature types and selecting the raw output format because it does not rely on post-processing assumptions about prevalence and sampling effort (Merow et al., 2013). As for *RandomForest*, we evaluated model uncertainty using bootstrapping with 50×500 random subsets of data points. We used permutation importance statistics to evaluate environmental variable contributions (Merow et al., 2013) and jackknife tests to determine which variables (a) contain the largest amount of useful information on their own and (b) result in the largest reduction in model performance (‘gain’) when excluded (Phillips, Anderson, & Schapire, 2006).

To compare agreement between the *RandomForest* and *MaxEnt* models we re-classified the output of both models into five percentile-based classes and compared the classification of each pixel by the two modelling methods (Arpaci, Malowerschnig, Sass, & Vacik, 2014).

3 | RESULTS

3.1 | RandomForest model output

The *RandomForest* habitat suitability model performed well on performance metrics including AUC score (0.92), Kappa score (0.71) and OOB estimate of error rate (13.7%). The latter means that when validated by withholding and predicting data in the training set, the model predicts class (presence-absence) incorrectly only 13.7% of the time.

Of the 31 environmental covariates, 13 were selected for inclusion in the model (Figure 2). Of these, distance to coast, distance to major roads and distance to inland water make the greatest contributions to model predictions according to the Genuer et al. (2010) variable importance metric. These are followed by elevation, soil clay content and topographic roughness (Figure 2). Two alternative



FIGURE 2 The importance of spatio-environmental predictors in determining the RandomForest model fit for sites in the Tasmanian Aboriginal Heritage Register. The variables are listed in descending order of importance, variable importance (VI) is calculated according to Genuer et al., (2010). "D to" denotes "distance to" and indicates proximity to a resource/habitat calculated as "cost distance" to account for the time and energy "cost" of a given traverse (Verhagen & Whitley, 2012)

D ROADS
DCOAST
DIWATER
DEM2
CLAY
ROUGH1000
RIVALL
SLOPE
MINT CM2
D HEATHLAND
OrgC
D RAINFOREST
D EUCTALLWET
TPI

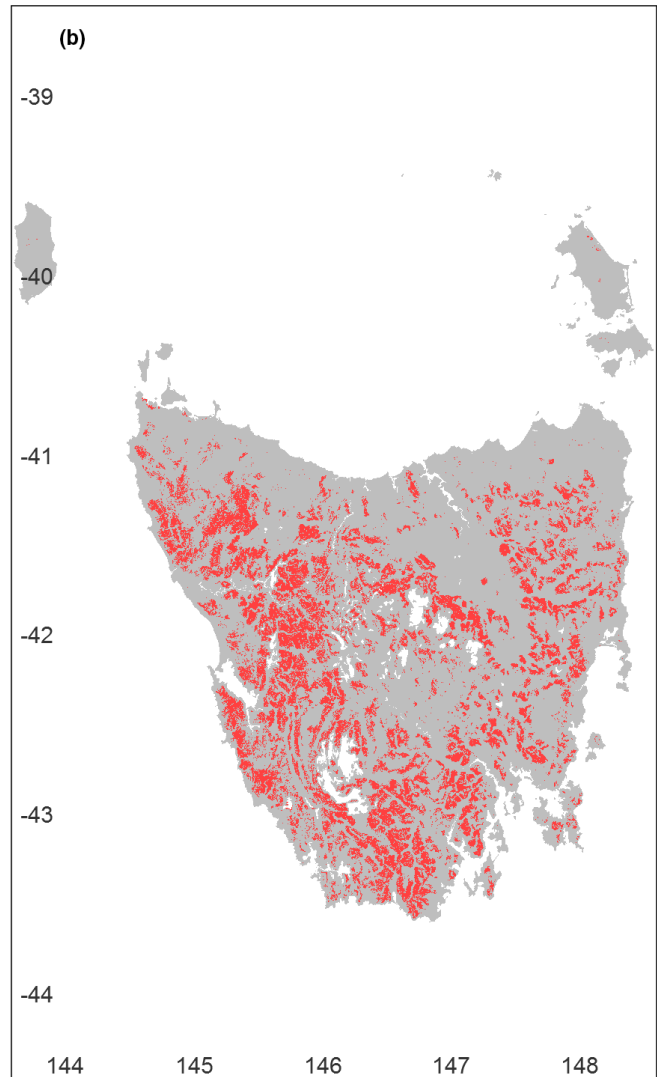
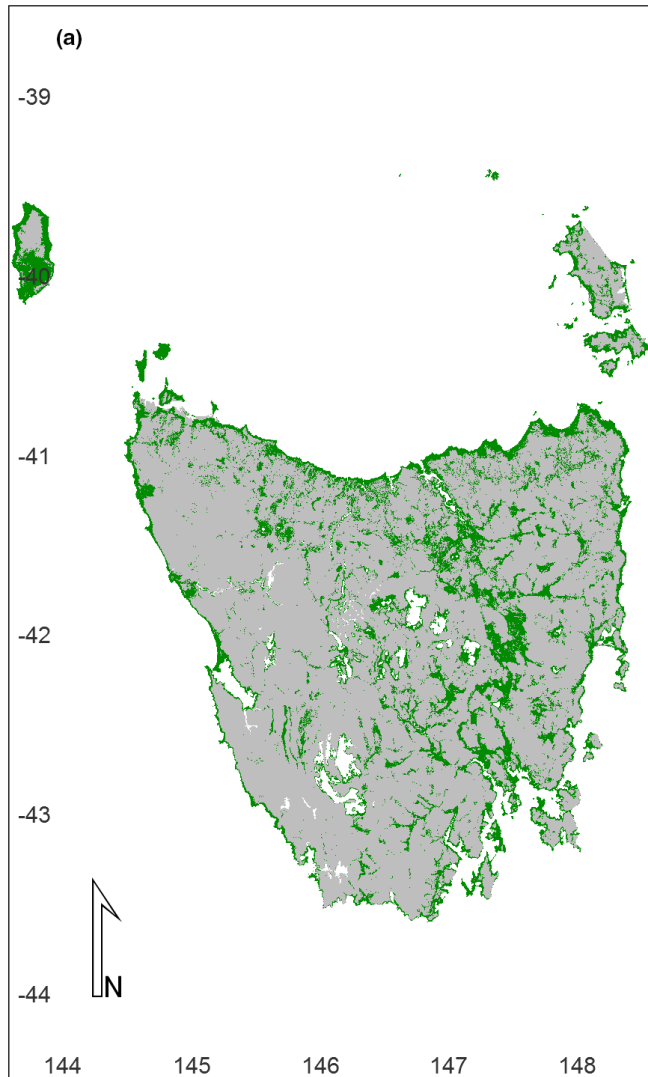
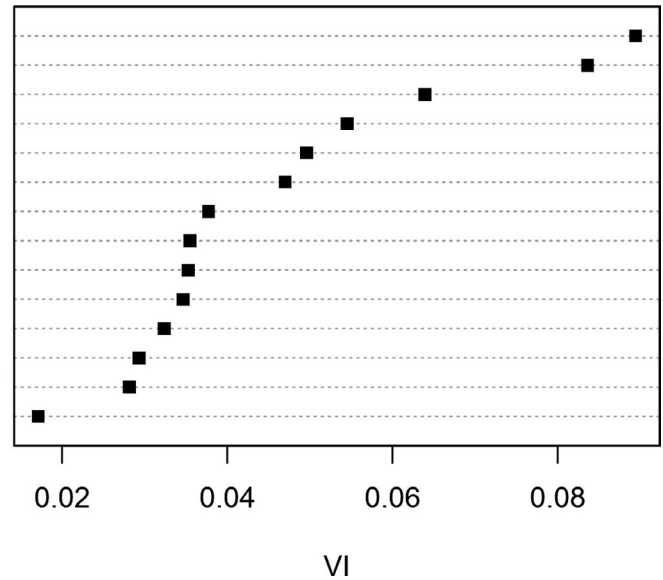


FIGURE 3 Distribution of the highest (green) and lowest (red) suitability grid cells according to a RandomForest model of Tasmanian Aboriginal archaeological artefact sites in the Tasmanian Aboriginal Heritage Register. The green 'high suitability' maps show the 20% of cells with the highest model scores; the red "low suitability" maps show the 20% of cells with the lowest model scores



Pre-1750 vegetation type ^a	State	MaxENT High	RF High	MaxENT Low	RF Low
<i>Eucalyptus</i> open forests with a shrubby understorey	23.19	25.08	27.26	17.70	18.93
<i>Eucalyptus</i> wet sclerophyll	15.12	16.71	11.99	12.59	9.84
Cool temperate rainforest	11.71	2.87	4.89	25.79	22.85
Sedgeland, rushes or reeds	9.81	3.68	6.42	15.87	18.67
<i>Eucalyptus</i> open forests with a grassy understorey	9.75	5.88	7.67	7.32	9.42
Low closed forest or tall closed shrublands	6.28	10.57	9.01	4.78	6.42
<i>Eucalyptus</i> woodlands with a shrubby understorey	5.35	9.28	9.04	0.33	0.76
<i>Eucalyptus</i> tall open forest with fine-leaved shrubby understorey	4.23	3.67	3.24	4.16	3.09
Heathlands	2.50	4.32	3.29	3.61	2.55
Temperate tussock grasslands	2.10	2.84	3.18	0.53	0.81
Other <i>Acacia</i> forests and woodlands	1.42	1.12	0.93	1.12	0.89
<i>Leptospermum</i> forests and woodlands	1.36	1.04	0.87	2.48	2.38
Unknown/no data	1.23	3.42	3.09	0.09	0.18
Other shrublands	1.14	2.34	1.86	0.23	0.08
<i>Eucalyptus</i> tall open forests and forests with ferns	1.11	1.17	0.84	0.52	0.33

^aVegetation designations for each pixel were sourced from the National Vegetation Information System Pre-1750 Major Vegetation Subgroups layer (Department of the Environment, 2014).

variable importance measures—mean decrease in accuracy and mean decrease in GINI—return very similar variable importance rankings (Fig. S1.2 in Appendix S1). The partial dependence plots (Figure S1.3 in Appendix S1) indicate that probability of presence tends to decrease with distance to coast, roads and inland water, as well as elevation. The relationship with clay content and topographic roughness is more complex, but, in general, a high level of topographic roughness is associated with a lower probability of presence.

Overall the model predicts distinct spatial patterns in the probability of archaeological site occurrence across the Tasmanian landscape. Figure 3 illustrates the key patterns, showing the distribution of the highest-scoring (highest habitat suitability) and lowest-scoring (lowest habitat suitability) 20% of cells. A map showing the full gradient of probability scores is in Figure S1.5 in Appendix S1.

The highest habitat suitability pixels (Figure 3a) are spatially concentrated around the coast (particularly the north), along several

major river valleys (Derwent, Tamar and Fingal), across the Midlands, and inland water bodies across the Central Plateau (see Figure 1 for region locations). Lower habitat suitability pixels (Figure 3b), are preferentially distributed along mountain ridges, the high alpine plateaus, the eastern uplands and parts of the lowland western interior. Bootstrapping analysis indicates that the definition of the coast, major river valleys, Midlands and Central Plateau lakes as high probability areas is robust, with >80% of 50 bootstrap runs predicting presence across these areas (Figure. S1.4 in Appendix S1).

3.2 | Biogeographical analysis of high and low suitability landscapes

Figure 4 shows the distribution of the highest (top 20%) and lowest (bottom 20%) probability cells along four major environmental gradients (cost distance to coast, elevation, mean annual precipitation

TABLE 1 Proportions of modelled pre-1750 vegetation communities in pixels classified as high (top 20%) and low (bottom 20%) suitability habitat by MaxENT and RandomForest models of artefact sites in the Tasmanian Aboriginal Heritage Register. Only vegetation types present over greater than 1% of Tasmania are shown (see Table S1.2 in Appendix S1 for the full table)



and mean annual temperature), compared to all grid cells across Tasmania. While both the high and low suitability cells stretch along the full length of environmental gradients, there is a clear over-representation of high suitability cells in coastal, lower elevation environments which tend to be relatively warm and dry. For example, although there are high probability cells at elevations up to 1,200 m, a large majority fall into the <250 m range.

There are also clear patterns in vegetation community (defined as pre-1750, that is, pre-European vegetation). In absolute terms, the most prevalent vegetation communities in high suitability cells are open shrubby eucalypt forest and wet sclerophyll forest, followed by eucalypt woodland (Table 1). The most prevalent communities in low suitability cells are cool temperate rainforest, open shrubby eucalypt forest, open grassy eucalypt forest and wet sclerophyll. Importantly, however, the strong representation of (a) open shrubby and (b) wet sclerophyll forest in both high and low suitability pixels largely mirrors their strong representation across the state overall: with neither community strongly over or under represented in high or low suitability categories. In contrast, eucalypt woodlands are twice as strongly represented in high suitability habitats than across the state and almost un-represented in low suitability habitats, indicating that site presence is actively biased towards this vegetation type. Heathlands, tussock grasslands, low closed forests/tall

shrublands and shrubby eucalypt forests are also over-represented in high suitability habitats, although to a lesser degree. Rainforests and *Leptospermum* forests are strongly over-represented in low suitability pixels.

3.3 | MaxEnt cross-validation

There is a high level of congruence between the RandomForest and MaxEnt output in terms of both habitat suitability prediction and variable importance. A side by side map of the two models, a model agreement map and full details of the MaxEnt output are available in Appendix S1.

Similar to RandomForest, the MaxEnt model highlights the coast, Midlands and Derwent, Tamar and Fingal valleys as areas with dense concentrations of highly suitable habitats. Low probabilities of site occurrence are concentrated in the west and alpine areas, Eastern Tiers, and parts of the Central Plateau (Figure S1.5 in Appendix S1). Figure S1.6 in Appendix S1 shows the agreement or disagreement of the two models for each pixel, based on a re-classification of the outputs into five categories of increasing probability (based on the 20th, 40th, 60th and 80th percentiles). The results show that the vast majority of pixels are placed into the same probability category by both models, indicating that our overall results are robust to specific modelling technique.

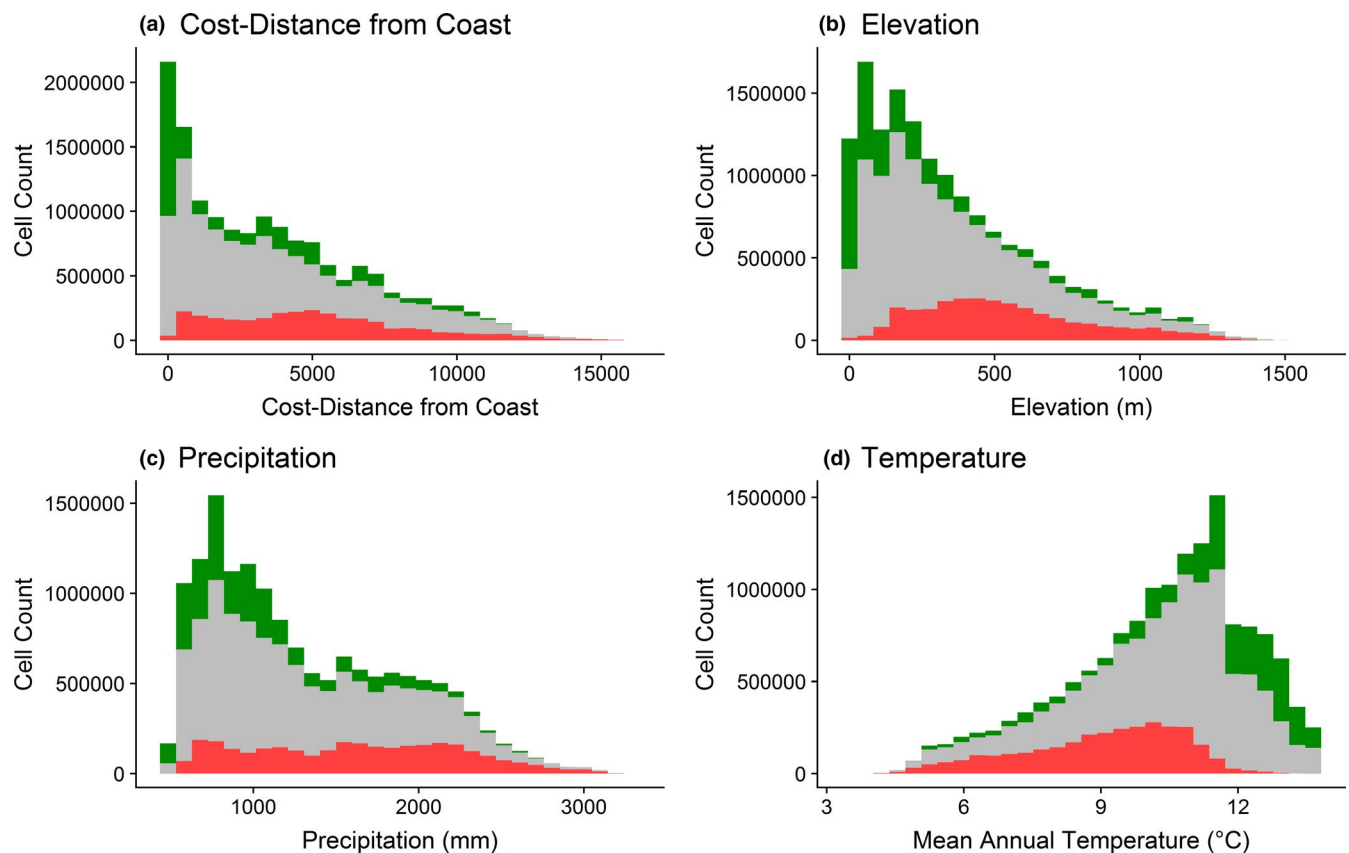


FIGURE 4 Distribution of the highest (green) and lowest (red) suitability grid cells along gradients of distance to coast (calculated as cost distance), elevation, mean annual precipitation and mean annual temperature, superimposed on the distribution of all grid cells across Tasmania. High suitability grid cells were defined as the 20% of cells with the highest model scores; low suitability grid cells were defined as those with the lowest 20% of model scores in a RandomForest model of artefact sites in the Tasmanian Aboriginal Heritage Register



The major areas of difference are the northern and north-western hinterland (where MAXENT tends to produce the higher probabilities) and specific patches of the west, far south-west and Eastern Tiers, where RandomForest tends to predict a higher probability of site presence.

The most important variables in the MAXENT model were also very similar to those for RandomForest, although in MAXENT elevation plays a stronger role. Distance to coast, elevation, distance to inland water and distance to roads were the most important variables according to permutation importance scores (Table S1.1 in Appendix S1). The jackknife tests indicate that topographic roughness, elevation, distance to coast and distance to roads produce the highest model gain when used in isolation, implying that these variables contain the most useful information on their own (Figure S1.7 in Appendix S1). Distance to coast had the greatest decrease in gain when omitted from the model; it thus has the most information not present in the other variables.

Key trends in the marginal response curves (Figure S1.8 in Appendix S1) are very similar to those in the RandomForest partial dependence plots and indicate that probability of the presence tends to decrease with increasing distance from coast, elevation, slope and topographic roughness.

4 | DISCUSSION

4.1 | Which types of landscape have the greatest (and least) archaeological evidence for Tasmanian Aboriginal occupation?

Our habitat suitability analyses of the most comprehensive database of Tasmanian archaeological sites produced a coherent biogeographical regionalization of the island of Tasmania. Our RandomForest model achieved strong performance metrics, and the biogeographical patterns (Figures 3 and 4) were supported by our MAXENT cross-validation (Figure S1.5 in Appendix S1). Our results can, therefore, be considered a robust platform from which to characterize those landscapes with the most, and least archaeological evidence for Tasmanian Aboriginal utilization.

In general, those landscapes with the *most* material evidence for Tasmanian Aboriginal presence can be characterized as: (a) virtually any coastal landscape; and (b) particular types of inland location, specifically those that are flatter, drier, lower elevation (<450 m) and/or adjacent to some form of inland water (Figure 4, Figure S1.3 in Appendix S1). They can support any vegetation type but are most often tall closed shrubland or open shrubby forest on the coast, or open shrubby forest, wet sclerophyll forest or open grassy forest inland. They are more likely to have soils with a high proportion of clay (Figure S1.3 in Appendix S1). Overall, this means we can characterize those landscapes with most evidence for resource utilization by Tasmanian Aboriginal people as inland river valleys, floodplains, wetland margins, open forest habitats, open plains and the coastal fringe. With appropriate caveats, these findings can be interpreted as a preference for Tasmanian Aboriginal people to occupy these types of ecological niche.

Landscapes with the *least* evidence for Tasmanian Aboriginal utilisation can be characterized as inland locations that are: (a) high elevation; (b) steep; (c) wetter and/or (d) topographically rough. A sizeable proportion is rain forest, open shrubby forest, wet sclerophyll forest or sedgeland. Notably, they are definitively *not* woodland landscapes.

4.2 | What are the ramifications for existing theoretical models of Holocene Tasmanian Aboriginal activity?

Many aspects of our results provide landscape-scale analytical support to previous theories of Holocene Tasmanian Aboriginal activity—largely founded on regional archaeological investigations, ethnographic research and traditional knowledge (e.g. Cameron, 2011; Cosgrove, 1999; Kee, ; Kee, 1990). Our modelling clearly supports the importance of coastal and inland waterways as hubs of Tasmanian Aboriginal activity (e.g. Cameron, 2011; Cosgrove, 1999; Kee, ; Kee, 1990), with distance to coast and distance to inland water among the most important predictors of site presence (see Figure 2). We find a strong preference away from rainforest habitats and towards woodlands (Table 1): congruent with the prevailing hypothesis that Tasmanian Aboriginal people preferred (and potentially promoted) more open vegetation structures (Folco & Kirkpatrick, 2013; Gammage, 2011; Jones, 1969). In the north-east, our results support Cameron's (2011) elegant reconstruction of a coastal and flat hinterland-oriented economy with less intensive, but still active, use of particular upland domains.

Vegetation-based variables ranked low in all variable importance analyses, and—with the notable exceptions of rainforest and open woodland—most vegetation types are distributed across both high and low suitability habitats in proportions closely analogous to their distribution across the state (see Table 1, further detail available in Table S1.2 in Appendix S1). Thus overall, vegetation type appears to be a less important predictor of site suitability for artefact occurrence, suggesting physical aspects of the landscape (slope, clay, and distance to coast and/or inland water) may be due greater attention in narratives about Tasmanian Aboriginal landscape use. This novel finding challenges notions about the strong association, and dependency, of Tasmanian Aboriginal occupation on vegetation type. In particular, our modelling challenges ideas about Holocene usage of Tasmania's forest environments.

In Tasmania—and indeed many other parts of Australia—there is a tendency to assume that forests, in particular, wet sclerophyll and rain forests, were less resource rich and thus less utilized than woodland and grassland zones (e.g. Cameron, 2011; Cosgrove 1999; Dortch 2006, for an exception see Thomas 1992). While our results support a preference away from rainforest habitats, they suggest a more complex story with respect to other forest types. Wet sclerophyll *Eucalyptus* forest is well represented in both high and low categories, inconsistent with avoidance of this vegetation type. While challenging for Tasmania, this finding is in fact congruent with several studies from the south-eastern and southwestern Australian



mainland, which have found wet sclerophyll forests as much utilized as open forest (e.g. Bowdler 1983, Dortch 2006). Conversely, open grassy forests—often assumed to be the type of habitat strongly preferred by Aboriginal people (e.g. Gammage, 2011)—are in fact under-represented in our model's high suitability zones (Table 1). This latter finding appears to relate to the higher elevation of these open ecosystems, most of which are found on the Central Plateau (Figure 2), and cautions against an automatic association between open grassy formations and evidence for intensive Aboriginal landscape use, in Tasmania or elsewhere.

Our model also provides empirical evidence for the heterogeneity of landscapes which Tasmanian Aboriginal people occupied. Alongside the trends described above, our models show concentrations of high suitability pixels over a plurality of ecological niches that cover the full breadth of Tasmania's precipitation, temperature and elevation gradients. There are pockets of high habitat suitability pixels, for example, from the wet, cool rugged west coast, to the warm, dry north-east and the subalpine Central Plateau. High habitat suitability pixels are also represented across all major vegetation groups: wet and dry sclerophyll forest, woodland, tussock grassland, heathland and even, to some extent, rainforests and sedgeland. Together, this highlights the diversity and breadth of ecological niches that must be accounted for in palaeoecological, archaeological, land management and cultural heritage narratives.

4.2.1 | Constraints, potential and future directions for archaeological and biogeographical research

While we are confident that our results reflect the spatio-environmental characteristics of Tasmanian Aboriginal artefact sites located to date, two key limitations are important to discuss. First, the model presented here provides a biogeographical model of past Tasmanian Aboriginal activity as indicated by the documented archaeological record. This is the product of variable and imperfectly known archaeological visibility and survey effort, and while we applied a best-effort bias correction, these methods are not able to completely erase the influence of sampling bias—particularly without access to detailed sampling effort information (Fourcade, Engler, Rödder, & Secondi, 2014; Syfert, Smith, & Coomes, 2013). Our results are, therefore, best interpreted as an integrated reflection of survey effort, archaeological visibility and the true density of archaeological site occurrence across Tasmania. Indeed, we included distance to major roads as a predictor in our model to test the relationship between site presence and accessibility. We found distance to roads to be a strong predictor of site presence (Figure 2), noting that as well as remnant survey bias this could indicate real similarities between those landscapes favoured by Tasmanian Aboriginal people (river valleys, floodplains, wetland margins, open forest habitats, open plains and the coastal fringe) and those landscapes most conducive to European road building (as documented elsewhere in Australia, e.g. Kerwin, 2006). The latter hypothesis and the robustness of our overall results are supported by a sensitivity analysis that found almost identical patterns of probability across the island

when distance from roads was excluded as a predictor (Figure S1.9 in Appendix S1). The issue of survey bias does, however, have particular implications for our model's ability to resolve pressing questions of Aboriginal utilization of rainforest, which has to date, been subject to little survey effort (DPIPWE, 2012). Without more survey effort, habitat suitability modelling has limited capacity to distinguish whether their apparently low habitat suitability reflects the absence of presence, or the absence of archaeological documentation.

Second, these models integrate the distribution of archaeological sites that have accumulated over a long and ecologically varied past. This means that the model may blur or obscure significant changes in the landscape distribution patterns of human activity over time. For example, although we can assume with taphonomic basis that the *majority* of artefact sites in the AHR date from the mid-late Holocene, there are some important exceptions which must be accounted for in model interpretation. These include the patches of high suitability habitat in the inland south-west and the West Coast range, which reflect the spatio-environmental characteristics of key Pleistocene sites (Corbett, 1980; Cosgrove, Allen, & Marshall, 1990). There are also a number of important early Holocene sites in the data-set (e.g. Cosgrove, 1984). Until we are able to disentangle sites of different eras, these models will have limited capacity to test important hypotheses regarding shifting spatio-environmental distributions over time.

Despite these issues, our approach has provided robust insights into biogeographical patterns or Tasmanian Aboriginal archaeological sites. In partnership with the database custodians these patterns can be further refined by, for example, age-classifying subsets of the AHR data and matching these to hindcast models of climate and vegetation distributions layers in order to compare and contrast spatial and ecological patterns of Tasmanian Aboriginal land use through time (d'Alpoim Guedes et al., 2016; Franklin et al., 2015). If applied in such a strategic manner, habitat suitability models have the potential to be a nuanced and powerful landscape history tool with which to test hypotheses about shifting spatial and ecological distributions of Tasmanian Aboriginal people through time.

Habitat suitability modelling has been successfully used in other contexts, for example, New South Wales, Australia, to target little surveyed, but biogeographically promising, landscape zones (Ridges, 2010). Likewise our bias grids combined with our habitat suitability analysis can and should be used as a means of targeting less well-surveyed Tasmanian landscapes—both in spatial and in biogeographical terms—in order to develop a more holistic understanding of Tasmania's coupled human and environmental past. For instance, the limited understanding of the extent and nature of Tasmanian Aboriginal land use in the globally significant Tasmanian Wilderness World Heritage Area hampers the development of appropriate contemporary natural and cultural heritage conservation programs and effective fire management regimes (Press, 2016). In January 2019, lightning-ignited fires burnt extensive areas of the TWWHA; presenting a particularly important opportunity for using our modelling outputs and approach for systematic archaeological survey to resolve some of these critical questions in Tasmania's archaeological and ecological history.

In conclusion, this research draws out important features of Tasmanian Aboriginal artefact site distribution that open up new possibilities for well-informed debate about the nature and extent of cultural landscapes in Tasmania. Notwithstanding the caveats above, our modelling provides a spatially explicit tool that supports some, and challenges other, ideas about Tasmanian Aboriginal landscape use, and landscape burning. Importantly, our findings challenge archaeologists to develop more nuanced narratives of Tasmanian Aboriginal forest occupancy and utilization. They also challenge land managers by sending a strong message about the breadth and diversity of ecological niches utilized by Tasmanian Aboriginal people. Whether in archaeological, palaeoecological, conservation or cultural heritage contexts, our results clearly demonstrate that overly simplistic assumptions about Tasmanian Aboriginal habitat utilization are misplaced.

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DATA AVAILABILITY STATEMENT

All habitat suitability models generated for this study are available as a raster files (Arc Info ASCII, geographical coordinates with datum WGS 84), as are the rasters of model uncertainty. These can be requested from the corresponding author, or downloaded directly from this Dryad database: (doi:10.5061/dryad.jq05h33)

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BIOSKETCH

The research team, based at the University of Tasmania in the Environmental Change Biology group and Tasmanian Institute of Agriculture, is reconstructing a landscape history of Tasmania using a combination of observational, experimental and modelling techniques. A particular focus is the role of fire and other forms of Aboriginal land management.

Author contributions: D.M.J.S.B. and E.L. conceived the ideas; G.W. devised the methods and performed the modelling; P.J. analysed the data and led the writing; E.L., D.M.J.S.B. and G.W. contributed to the writing.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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